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FEEDBACK SYSTEM DESIGN.(U)
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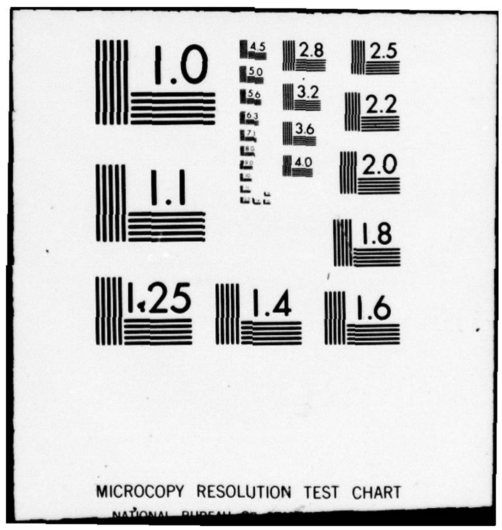
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

In Quantitative Feedback Synthesis, bounds on plant uncertainty and on the system performance are specified apriori. The minimum feedback is used which satisfies the latter over the range of plant uncertainty.

The principal effort during the past year was in extending Quantitative Feedback Synthesis to two new highly complex, multiple-loop, single input-output

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20. Abstract continued.

plant structural classes. The significant advantage of multiple-loop over single-loop is that , in highly uncertaint systems, the same performance specifications can be satisfied, with tremendously smaller sensor noise effects. A technique denoted as "Design Perspective" was developed, which enables the designer to evaluate the trade-offs without a detailed design. Thus, early in the game and before doing a detailed design, the designer can obtain an excellent idea of which loops (sensors) to use and which to omit and the portion of the "feedback burden" to assign to each loop. The same design techniques are applicable to highly uncertain nonlinear plants with the same structure.

Several complex detailed design examples with very large uncertainty were done. Design perspective results were very close to the final design results. The designs were simulated on the digital computer and in all cases satisfied the apriori assigned performance specifications.

Preliminary work was done on the problem of systems with highly uncertain nonlinear plants driven by nonmiminum-phase command inputs and disturbances. A synthesis philosophy was developed for solving this problem, but the detailed work is as yet not completed.

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ANNUAL REPORT - FEEDBACK SYSTEM DESIGN

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Summary.

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In Quantitative Feedback Synthesis, bounds on plant uncertainty and on the system performance are specified apriori. The minimum feedback is used which satifies the latter over the range of plant uncertainty.

The principal effort during the past year was in extending Quantitative Feedback Synthesis to two new highly complex, multiple-loop, single input-output plant structural classes. The significant advantage of multiple-loop over single-loop is that, in highly uncertain systems, the same performance specifications can be satisfied, with tremendously smaller sensor noise effects. A technique denoted as "Design Perspective" was developed, which enables the designer to evaluate the trade-offs without a detailed design. Thus, early in the game and before doing a detailed design, the designer can obtain an excellent idea of which loops (sensors) to use and which to omit and the portion of the "feedback burden" to assign to each loop. The same design techniques are applicable to highly uncertain nonlinear plants with the same structure.

Several complex detailed design examples with very large uncertainty were done. Design perspective results were very close to the final design results. The designs were simulated on the digital computer and in all cases satisfied the apriori assigned performance specifications.

Preliminary work was done on the problem of systems with highly uncertain nonlinear plants driven by nonminimum-phase command inputs and disturbances. A synthesis philosophy was developed for solving this problem, but the detailed work is as yet not completed.

RESEARCH IN FEEDBACK SYSTEM DESIGN

1. Introduction.

The primary purpose of this research is the development of a Quantitative Theory of feedback Systems. Feedback is mandatory when there is uncertainty in a system, but feedback theory has tended to be highly qualitative. Surely there should be a significant difference in the design of a feedback system where the plant parameter uncertaintly is by a factor of say x% , and one where it is 100x% ? However, there are very few design techniques in the literature which reveal this. Our objective has been to develop such a quantitative theory step by step, starting with the simplest structures. In such a quantitative theory the problem statement includes the bounds of the uncertain parameters and equally important, the tolerances on the system performance. The design steps should be related to these numbers and the final design which emerges should be tuned to the specifications.

2. Two New Complex Structures

Prior to this effort, the cascade structure of Fig. 1 was the most complex one for which Quantitative Design was available. Under AFOSR - 2946 sponsorship [3] (1977-78), it was extended to the structure consisting of two parallel branches, shown in Fig. 2. During the current year (1978-79), it was extended to the two structures shown in FIg. 3a,b. The first is denoted as the Triangular strucutre, the second as the Parallel-Cascade strucuture [9].

In each case there are given tolerances on the closed-loop system response, and the range of the plant uncertainty. For example, the following design is typical.

Numerical Example

Problem statement

(a) System structure: In Figure 3b, let $m=4$, $n_1=n_2=2$, $n_3=n_4=3$, giving Figure 4a.

(b) Plant: $P_{12} = \dfrac{k_{12}}{S(1+S/A)}$, $P_{11} = \dfrac{k_{11}}{S}$,

$$P_{22} = \frac{k_{22}}{S} \quad , \quad P_{21} = \frac{k_{21}(1 + S/z)}{S(S^2 + BS + C)} \quad ,$$

$$P_{ij} = \frac{k_{ij}}{S} \quad , \quad i = 3,4 \quad , \quad j = 1,2,3 \quad .$$

(c) Plant Uncertainty: $k_{11}, k_{21} \quad [4,40]$

$k_{12}, k_{22} \in [25,750]$

$k_{31}, k_{41} \in [4,20]$

$k_{32}, k_{42} \in [5,40]$

$k_{33}, k_{43} \in [5,75]$

$A \in [1,2]$, $z \in [1,2]$, $B \in [0,1]$

$C \in [0.04,1]$.

Specifications

(a) Bounds on unit step response $C(t)$ - shown in Fig. 4b

(b) Disturbance Response: $\left|\dfrac{L}{1+L}\right| \leq 2.3$ db .

Design Simulation The design details are given in Report 4 . Design simulation results are shown in Figs. 5a-d, for 40 representative number of plant parameter combinations, including the extremes. The specifications (Fig. 4b) are satisfied in all cases.

Sensor Noise Effects at plant input X , are compared in Fig. 6. $|X/N_1|^2_S(B)$ is for the case of a single-loop design which satisfies the same specifications. Note that scale B is used here. The effect is decreased tremendously in a multiple-loop design $|X/N_1|^2_{II,III}$ (A) - using scale A . The other curves give the effect of the other sensors - with scale A or B always used. If $G_{33} = G_{43} = 0$ in Fig. 4a then $|X/N_{12}|^2_{II}$ is applicable, whereas the smaller $|X/N_{12}|^2_{III}$ applied if G_{33}, G_{43} are used. Thus, one can decide whether this reduction is worth the extra cost of the two sensors and the construction of G_{33} , G_{43} . It is very useful that preliminary, highly accurate noise responses can be obtained fairly quickly, without a detailed design. This is next treated.

Design Perspective

Design Perspective is a very useful aid in practical design. A potentially multiple-loop plant has say n points including the plant output, at which sensors can be placed. Each sensor has its price which would vary according to its quality. The more costly the sensor , the less the noise associated with it. Say there is large plant uncertainty. Which sensors should be used? Should all n of them be used, or not at each point, and of what quality?

It is very desirable to get a good ball-park view of the trade-offs between the available loops, without having to try a number of detailed designs. This is precisely what Design Perspective provides. One first makes only a single-loop design for the problem, i.e. for the case only the plant output sensor is used. Based on this, Design Perspective permits the designer to very rapidly obtain very good approximations for the multiple-loop design in which all or some of the other sensors are used. This tells him quickly the relative importances of the various sensors, which can be omitted etc. Comparisons of exact and perspective designs for three examples are shown in Figs. 7a-c. In each case, the dashed lines are the Design Perspective loop transmission results, and the solid lines are the detailed design results. Clearly Design Perspective is extremely reliable.

3. Feedback systems with nonlinear plants and nonminimum-phase inputs

An exact synthesis technique was developed (I. Horowitz, Proc. IEEE Jan. 1976, pp. 123-130), for designing feedback systems with highly uncertain non-linear plants, to satisfy precise performance specifications. Proof of its validity requires knowledge of Banach spaces and Schauder's fixed point theorem. But design excution is conceptually very straightforward and can be done by frequency-response methods. The essence of the technique is the replacement of the nonlinear plant set $\mathcal{H}$ by a linear time invariant (ℓti) plant set $\mathcal{P}$, which is equivalent to $\mathcal{H}$ for the purpose of the problem. Then one must solve the resulting ℓti problem, and its solution is guaranteed to also solve the original nonlinear problem.

Up to now the acceptable plant outputs had to be minimum-phase (mp), in order to guarantee that all $P \in \mathcal{P}$ are mp. (We are assuming that the nonlinear plant is inherently mp, defined by its ℓti equivalent being mp for mp plant outputs). An inherently mp nonlinear plant can have a non-mp ℓti equivalent if the plant output is assumed non-mp. If so, our design procedure may break down, because it may not be possible to solve the resulting equivalent ℓti design problem.

We have been able in practice to solve such problems, but had no rigorous theoretical justification. But now we believe to have one. It involves equivalent ℓti plants which have both poles and zeros in the right half-plane (rhp). Normally, the feedback capabilities around such plants are severely limited [7], if the closed-loop system is to be stable. However, in our approach, large feedback is used anyhow, leading to a characteristic polynomial with rhp zeros. A ℓti system would then be unstable. However, the nonlinear system is stable. The mathematical details are being currently developed.

Journal Ppaers Published or Accepted - Supported by AFOSR - 76 - 2946

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2. Synthesis of linear time-varying nonminimum-phase feedback systems with plant uncertainty, I. Horowtiz and M. Sidi, Int. J. Control, 27, 1978, pp. 351-359.

3. A synthesis theory for a class of multiple-loop systems with plant uncertainty, I. Horowitz and T. Wang, Int. J. Control, 29, 1979, pp. 645-668.

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6. Blending of uncertaint nonminimum-phase plants for elimination or reduction of nonminimum-phase property, I. Horowitz and A. Gera, Int. J. Systems Science 1979 (proof corrected).

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8. Quantitative synthesis of uncertain cascade feedback systems with plant modification, I. Horowitz and B. Wang, accepted for publication in Int. J. Control 1980.

9. Quantitative synthesis of multiple-loop feedback systems with large uncertainty, I. Horowitz and T.S. Wang, accepted for publication in Int. J. Systems Science 1980.

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1. Reduction in the Cost of Feedback in Systems with Large Plant Uncertainty, P. Rosenbaum and I. Horowitz, 1977, 202 pages.

2. Synthesis of Oscillating Adaptive Systems, A. Shapiro and I. Horowitz, 1977, 294 pages.

3. Synthesis of Multiple-Loop Feedback Systems with Plant Modifications, B.C. Wang and I. Horowitz, 1978, 268 pages.

4. Quantitative Synthesis of Multiple-Loop Feedback Systems with Large Plant Uncertainty, T.S. Wang and I. Horowitz, 1979, 191 pages.

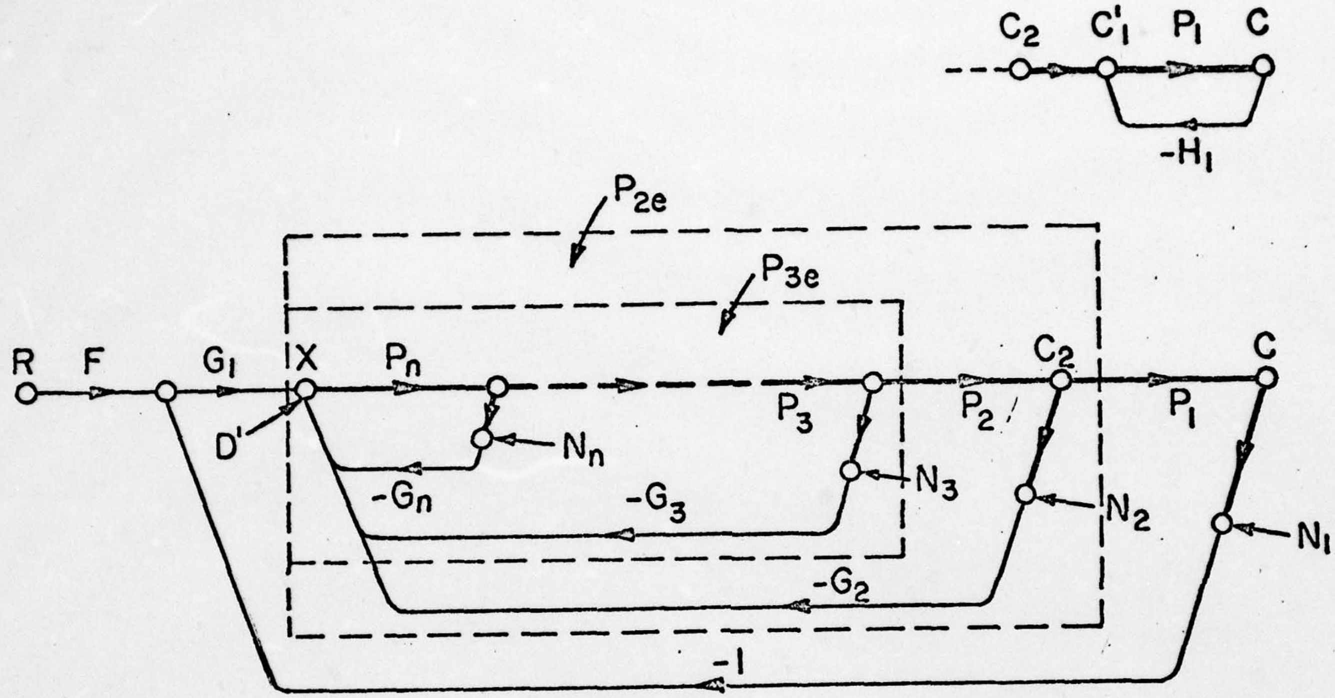


Fig. 1 A canonical feedback structure for a cascade plant.

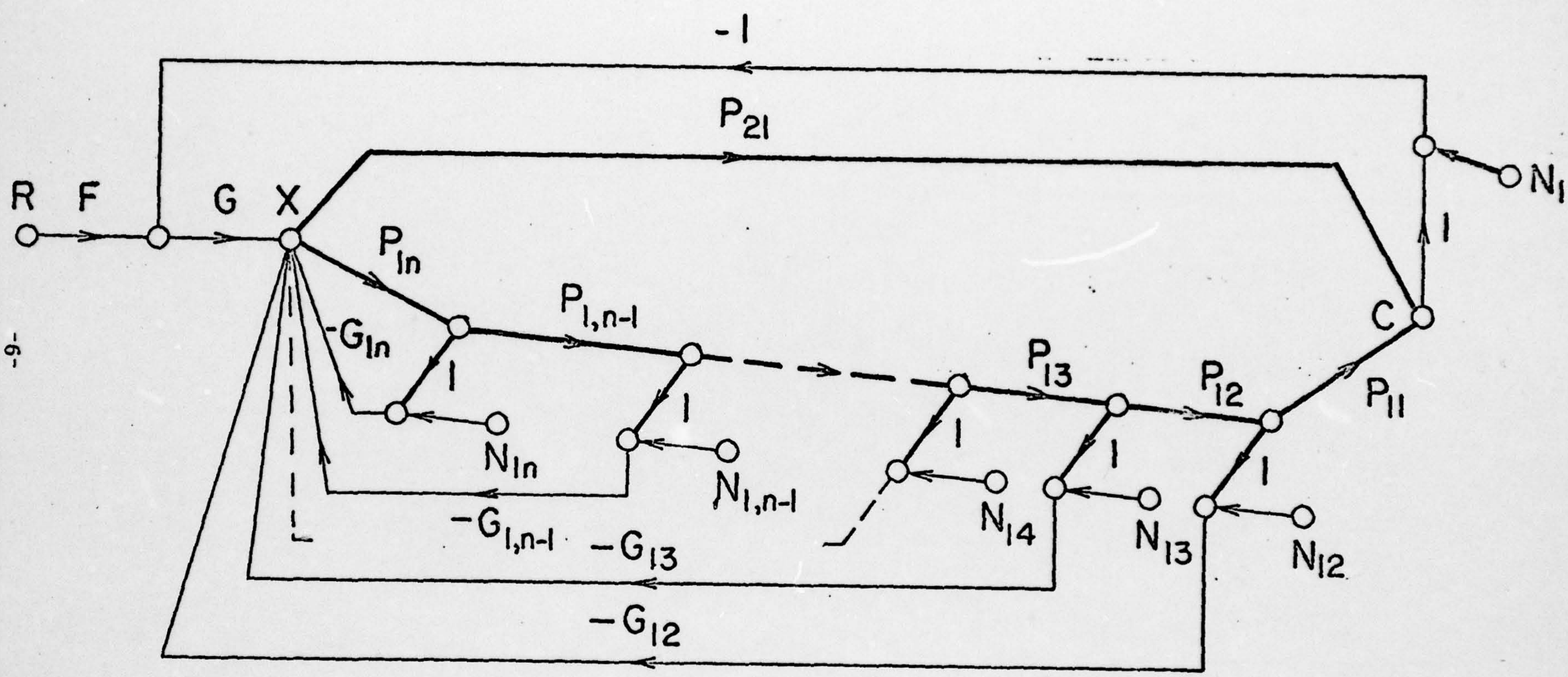


Fig. 2 A canonical feedback structure for plant of two parallel branches, one cascaded

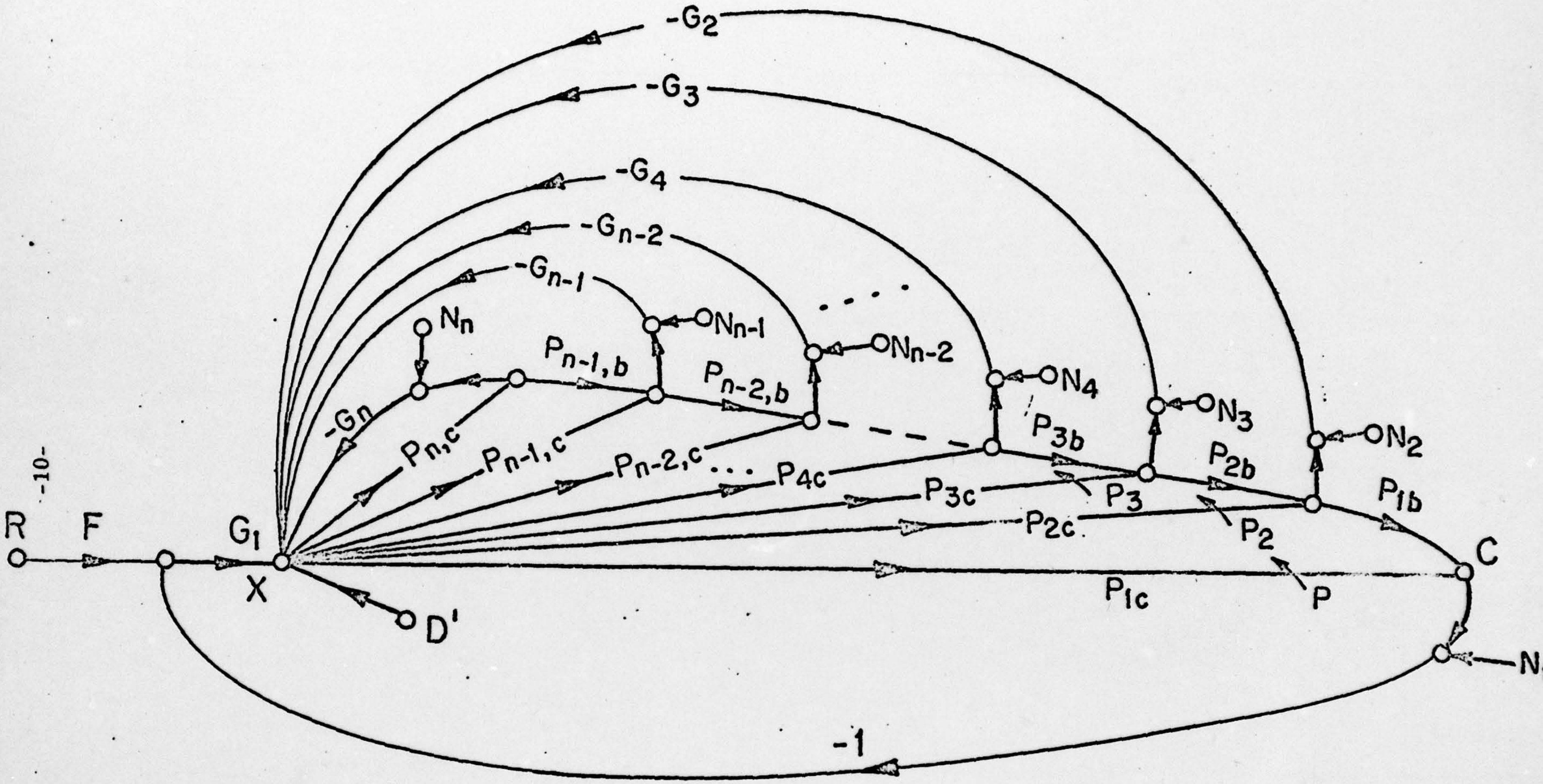


Fig.3a A canonical feedback structure for the general triangular plant

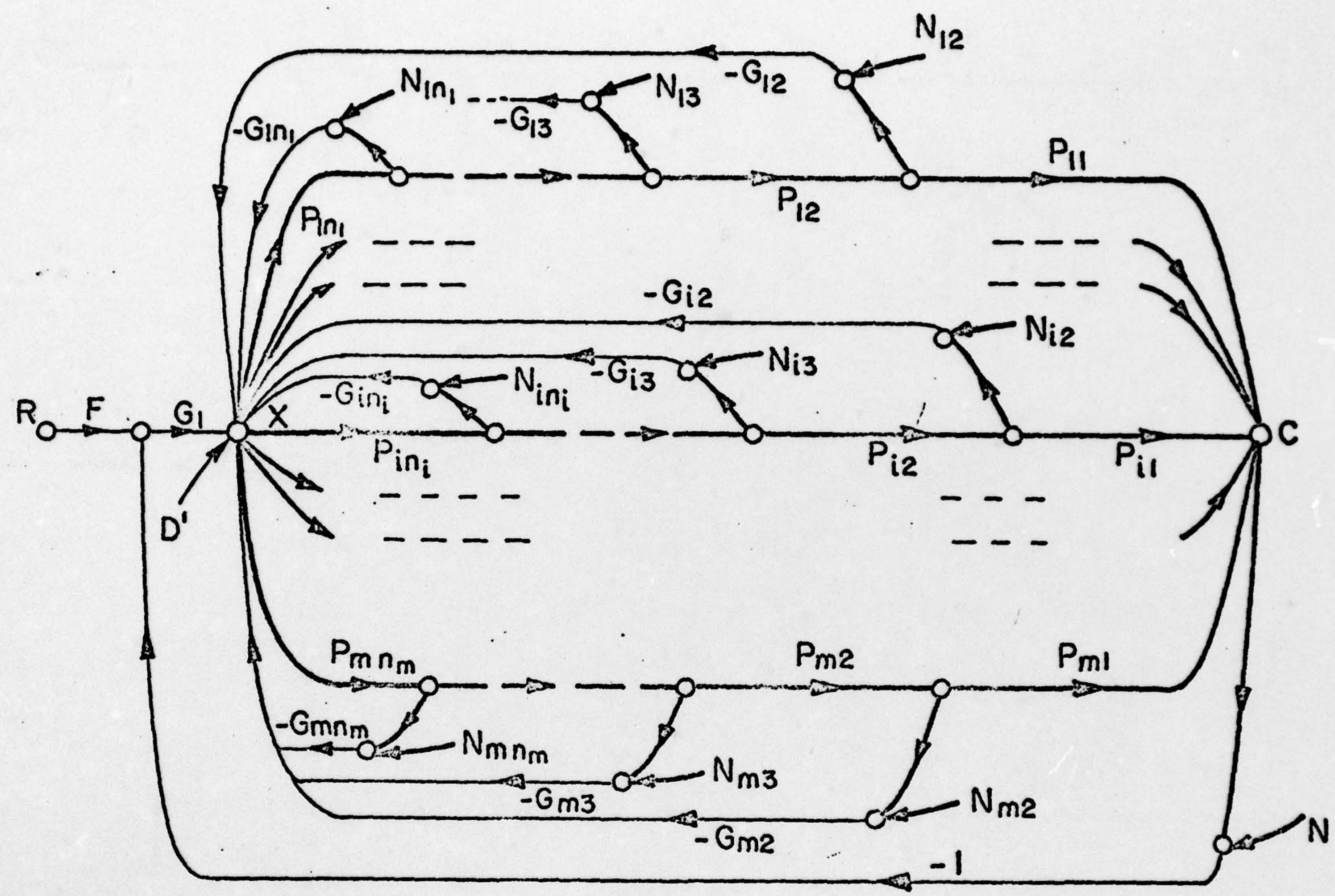


Fig. 3b A canonical feedback structure for the general parallel-cascade plant

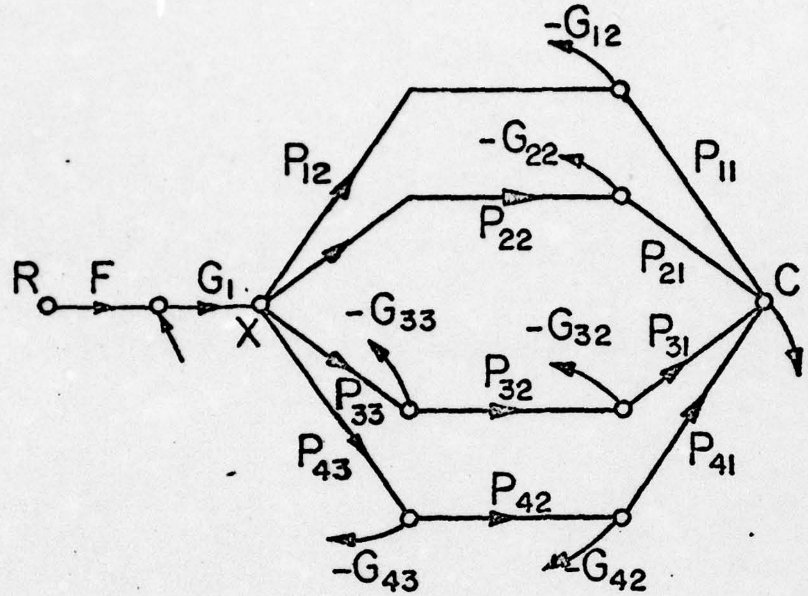


Fig. 4a Numerical example

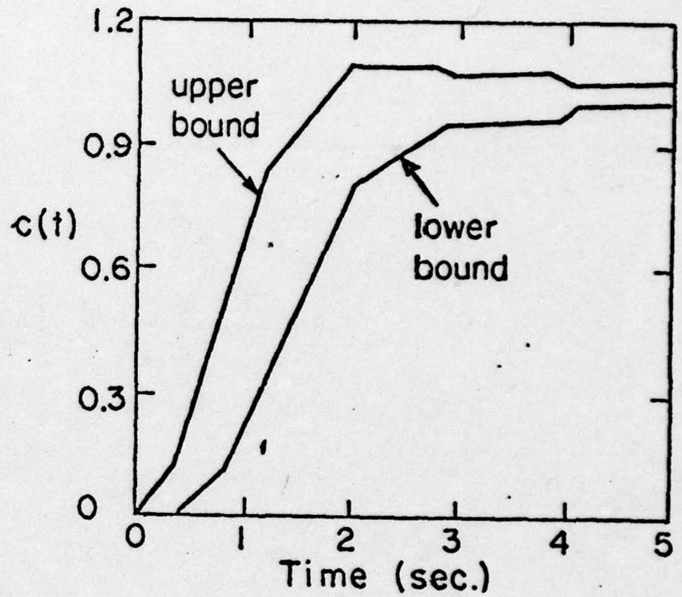


Fig. 4b Step response tolerances

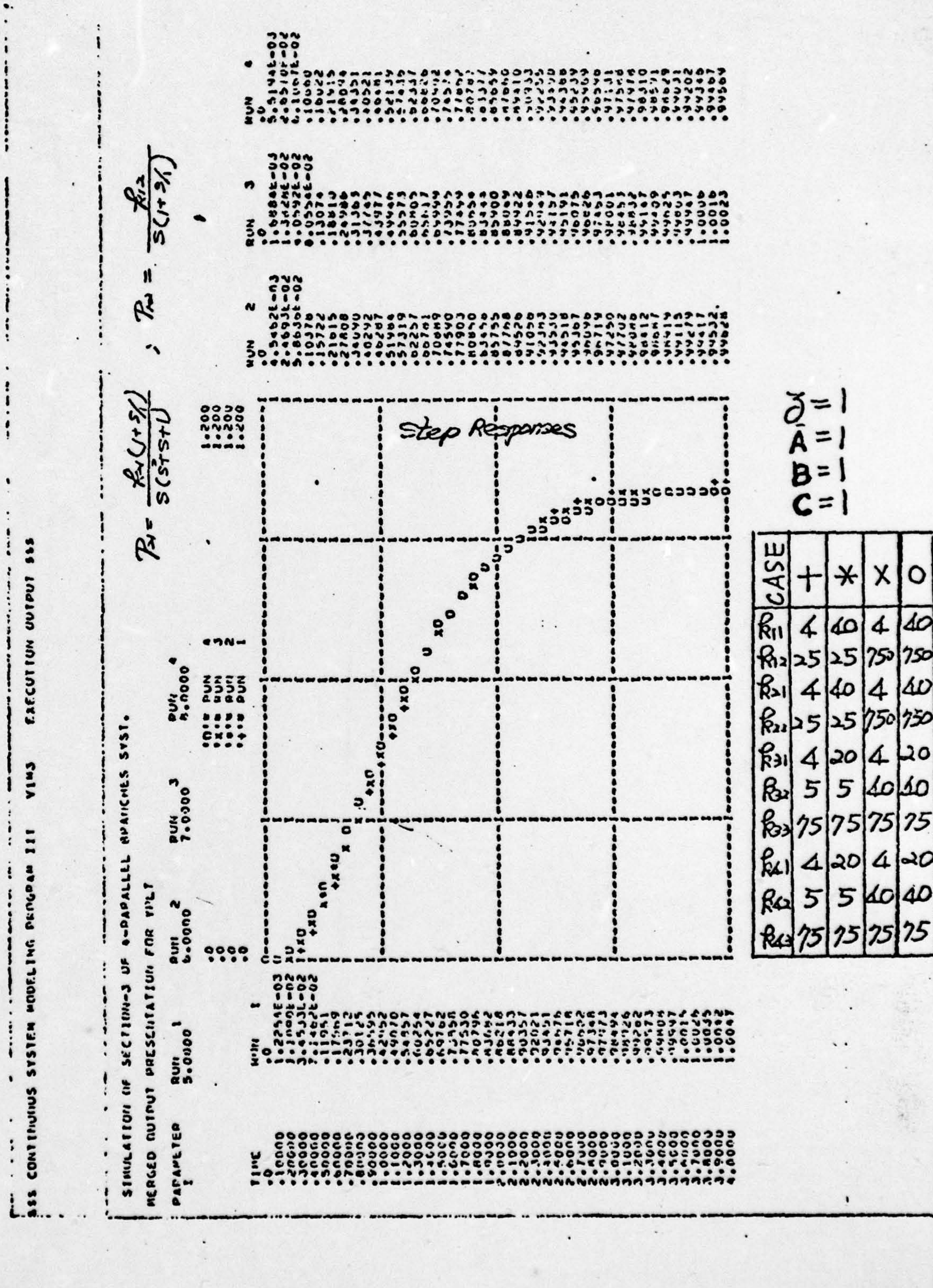


Fig. 5a Simulation results of step response.

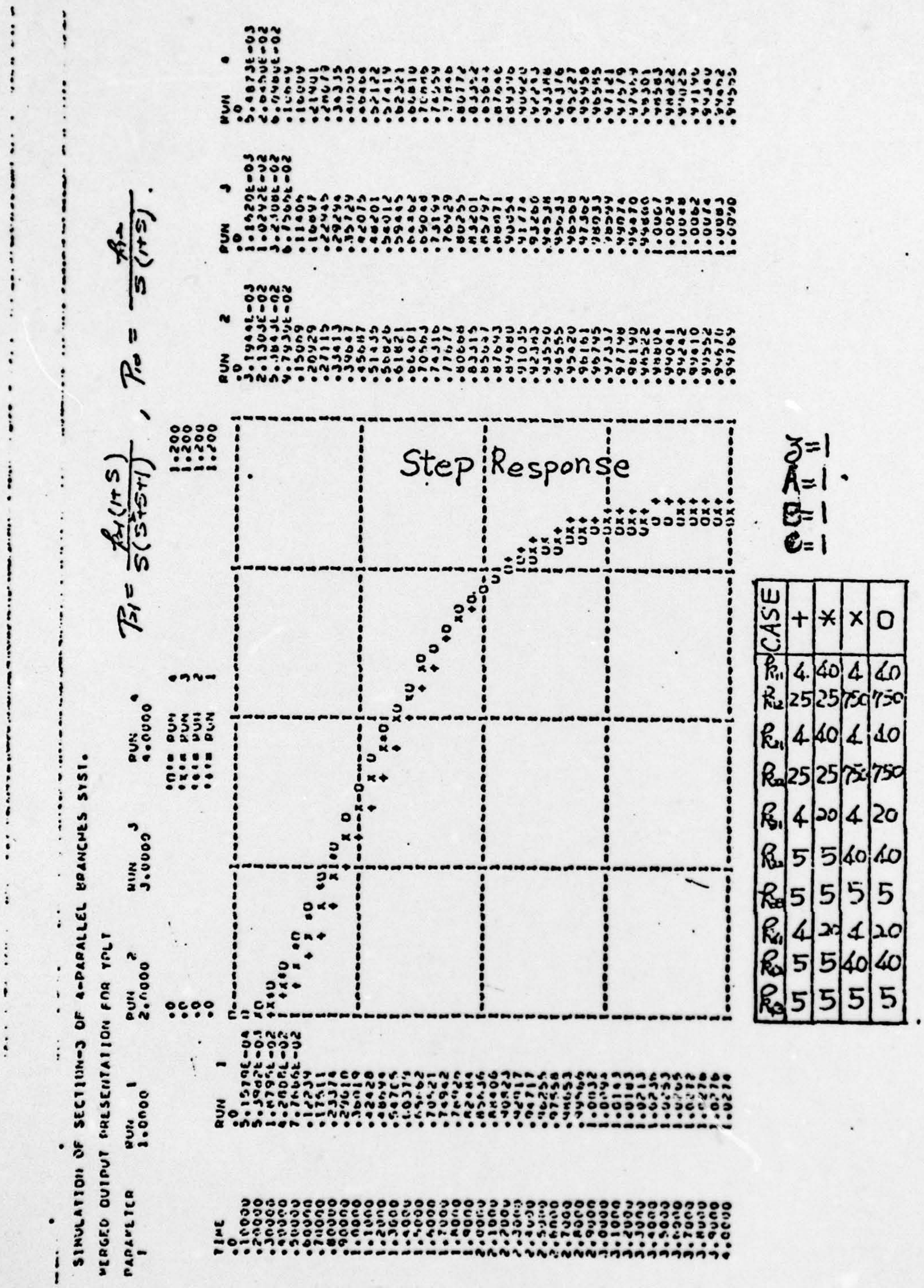
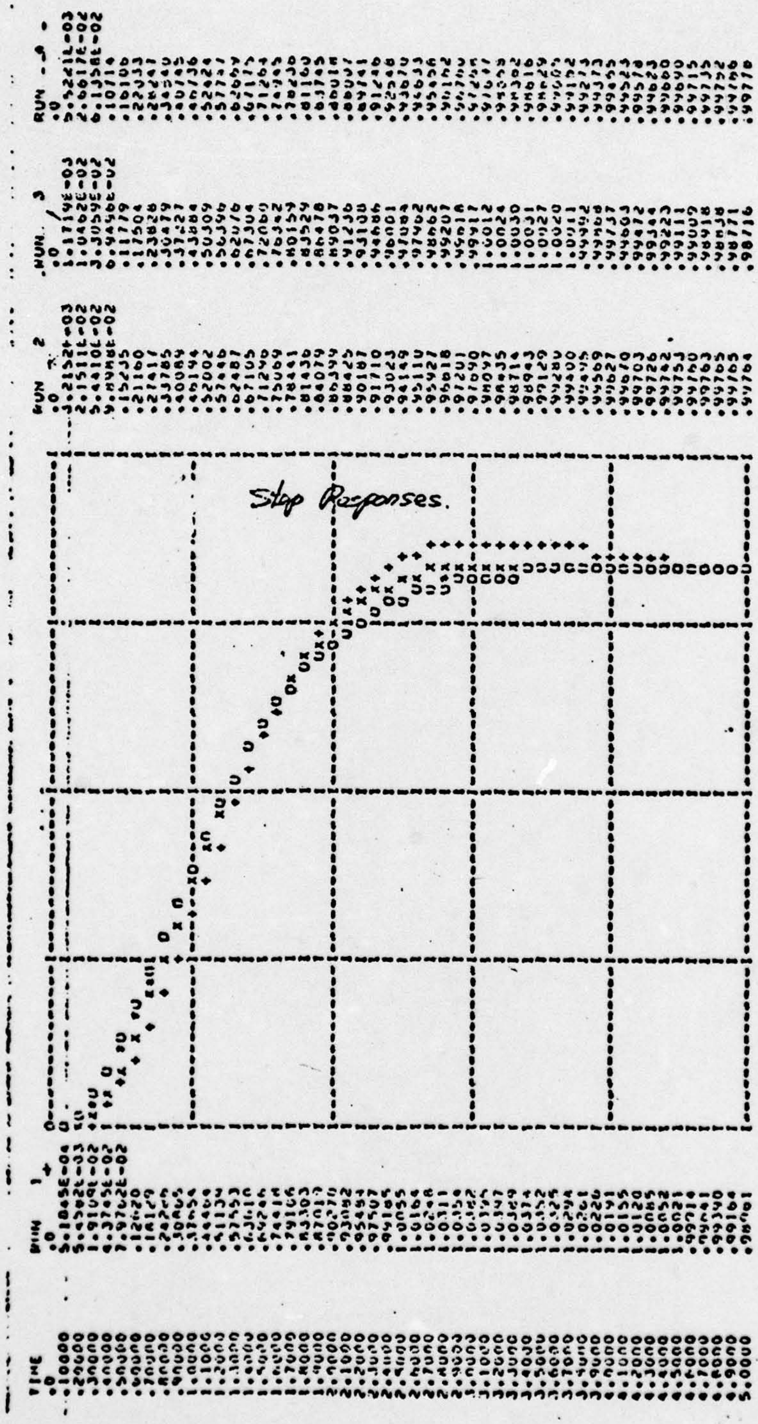


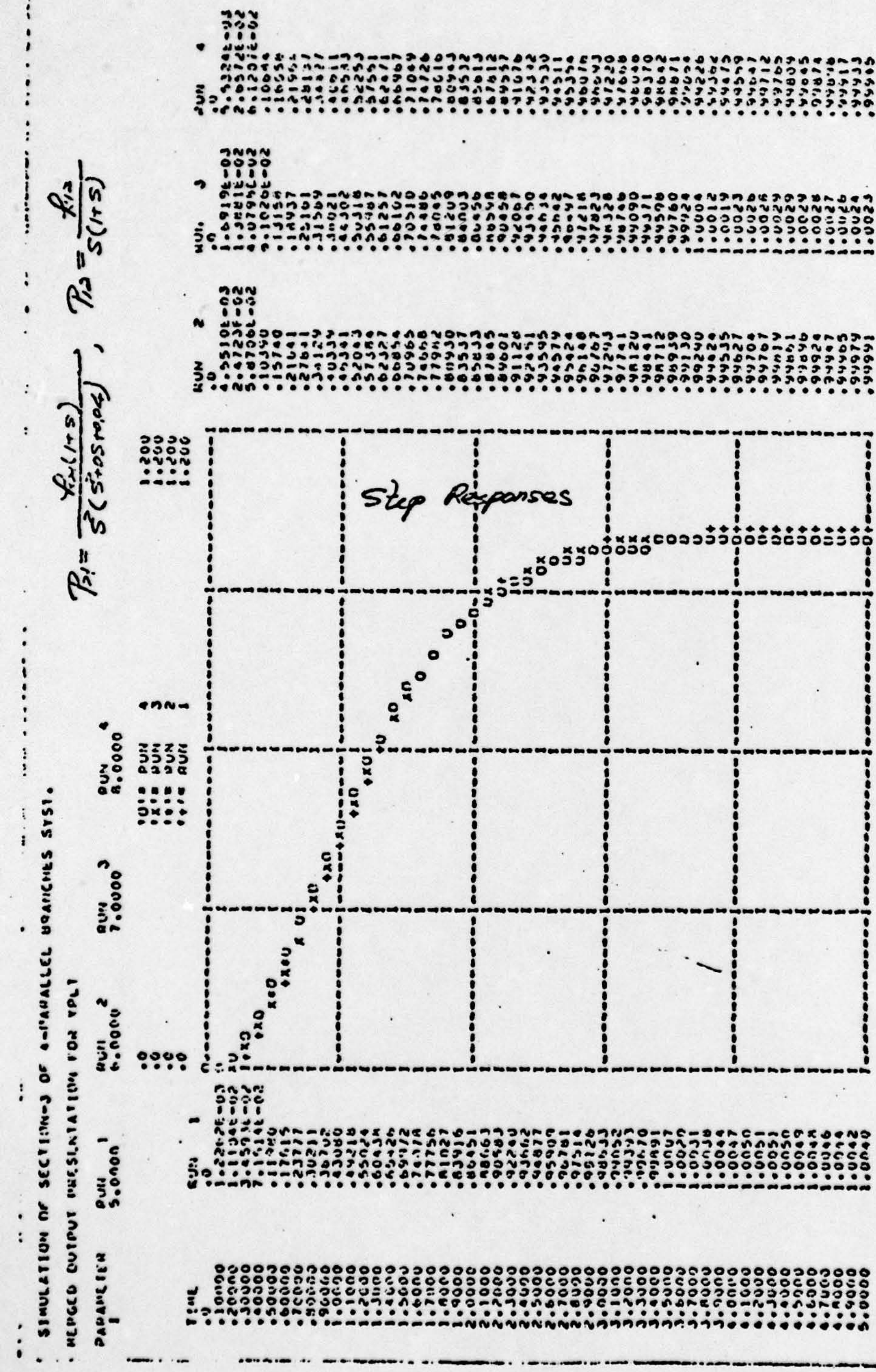
Figure 5-b Simulation results of step response.



$\zeta = 1$
$A = 1$
$B = 0$
$C = .04$

CASE	+	*	x	O
R_{11}	4	40	4	40
R_{12}	25	25	750	750
R_{21}	4	40	4	40
R_{22}	25	25	750	750
R_{31}	4	20	4	20
R_{32}	5	5	40	40
R_{33}	5	5	5	5
R_{41}	4	20	4	20
R_{42}	5	5	40	40
R_{43}	5	5	5	5

<u>Figure 5-c .</u> Simulation results of step response.



$\zeta = 1$
A=1
B=0
C=.04

CASE	+	*	x	O
R_{11}	4	40	4	40
R_{12}	25	25	75	750
R_{21}	4	40	4	40
R_{22}	25	25	750	750
R_{31}	4	20	4	20
R_{32}	5	5	40	40
R_{33}	75	75	75	75
R_{41}	4	20	4	20
R_{42}	5	5	40	40
R_{43}	75	75	75	75

Figure 5d Simulation results of step response.

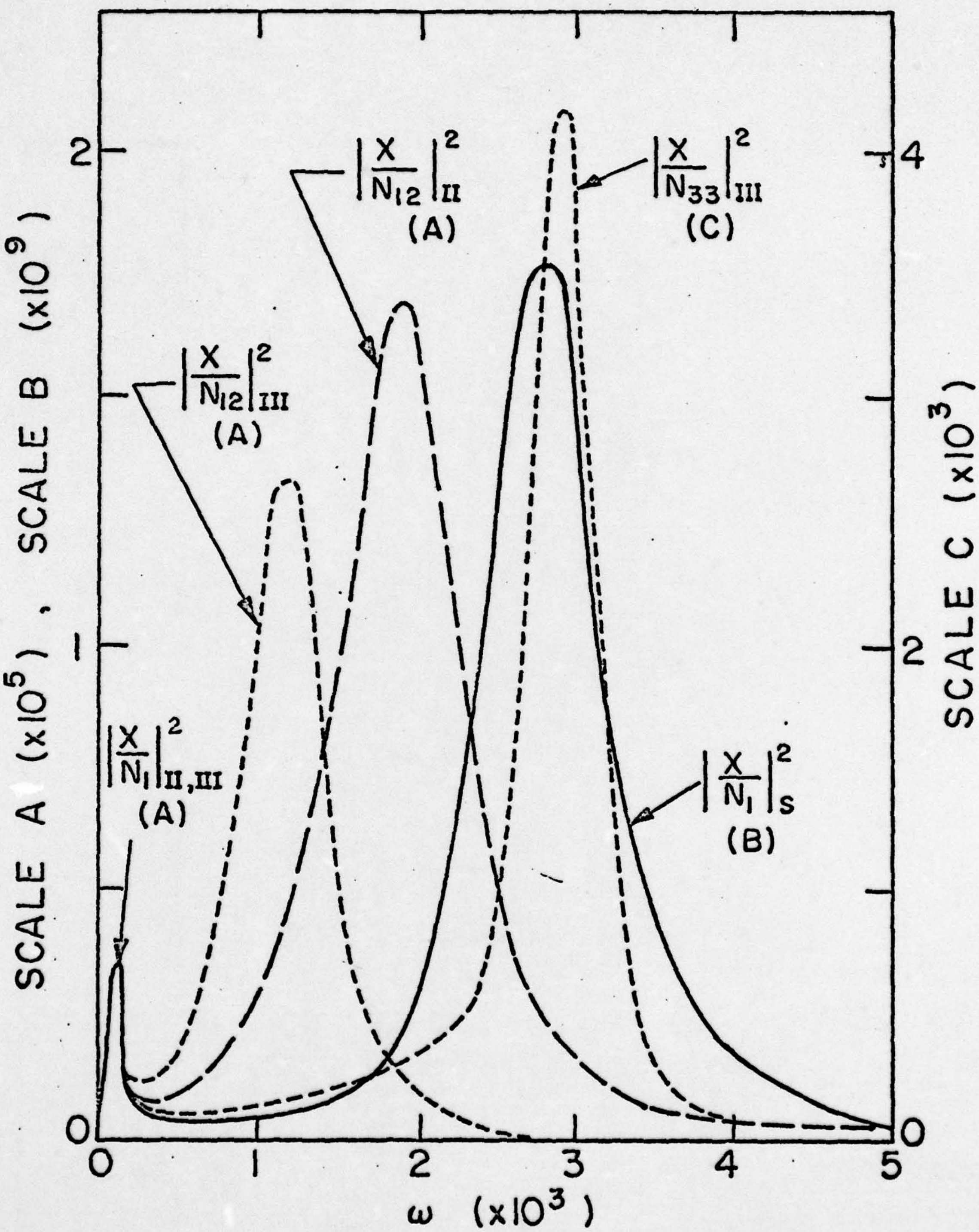


Fig. 6 Comparison of sensor noise effects at plant input X .

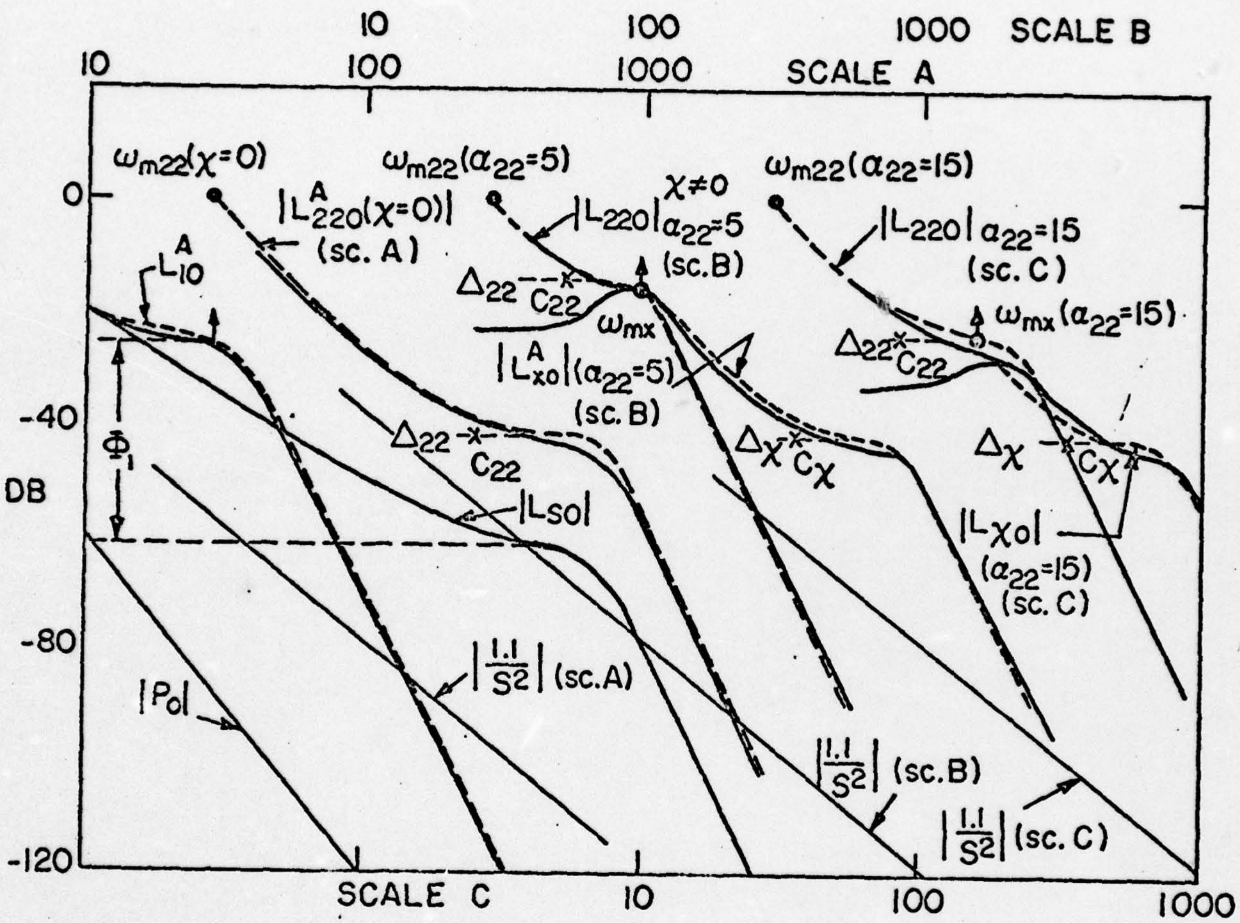
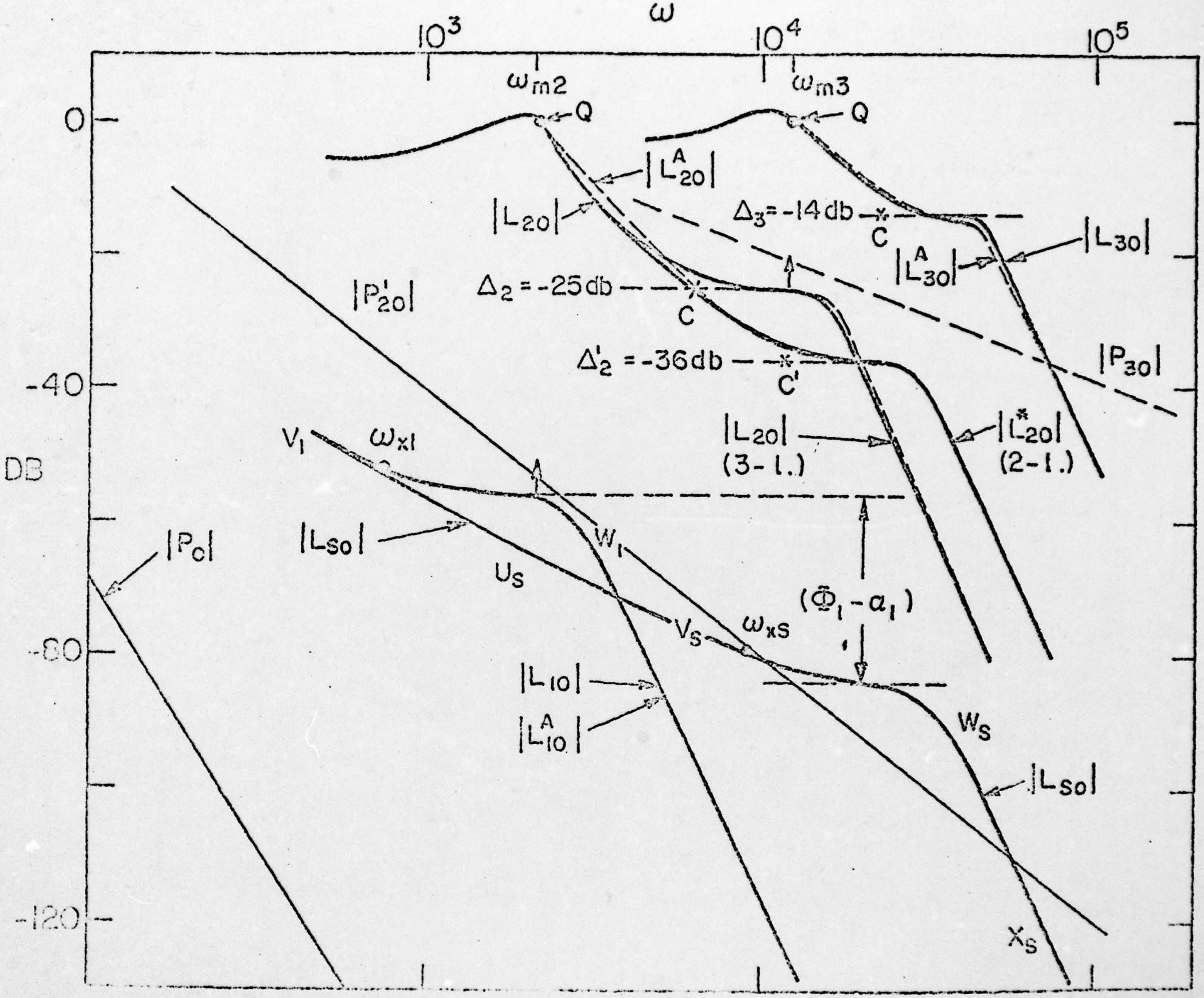


Fig. 7a Comparison of Design Perspective (dashed lines) with detailed design.

Fig. 7b Comparison of Design Perspective (dashed lines) with detailed design



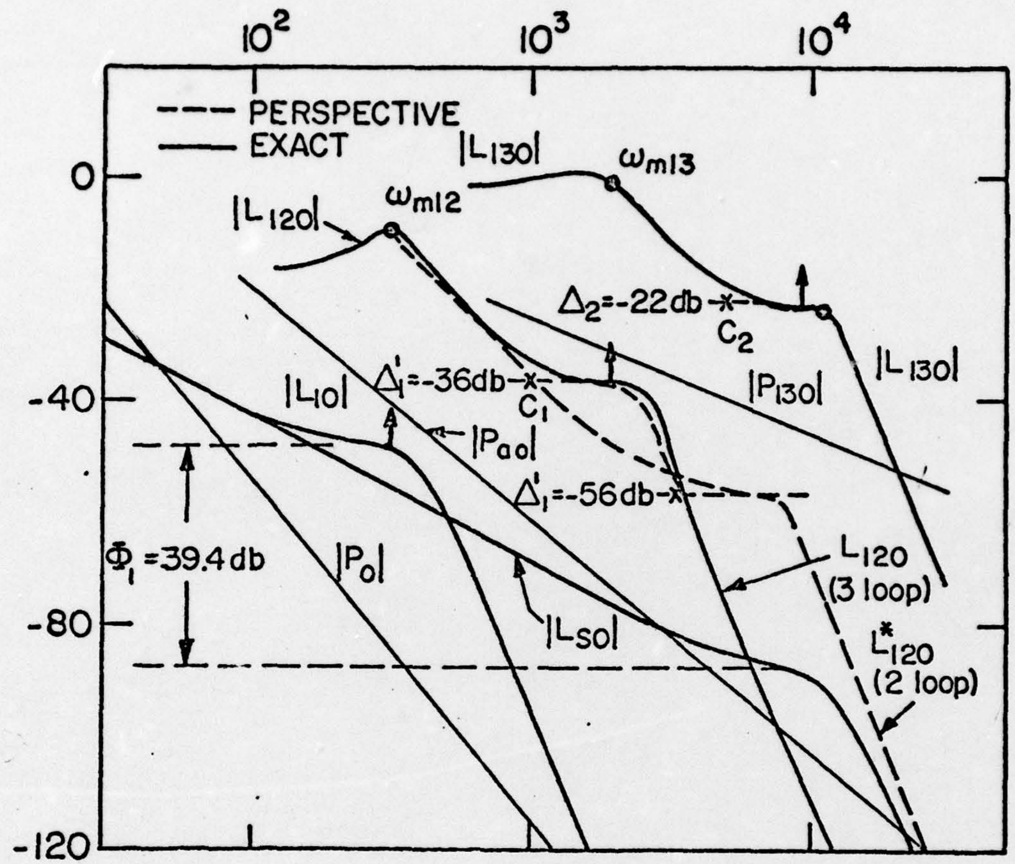


Fig. 7c Comparison of Design Perspective (dashed lines) with detailed design.